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HEALTH & SAFETY LABORATORY

Final report for R42:70: Quantitative measurement of asbestos and other fibres in bulk materials

IR/L/MF/98/02

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Sheffield Information Centre, IAS 4 (2)

Available to the public.

HSE Authorising Officer: R.Warner

HSL Report Approval	B.Tylee
Date of issue	August 1998
Job number	R42:70
Registry file	3CR/012/95
AmiPro File	H: Reports\R4270\\FP1

HEALTH AND SAFETY LABORATORY

SUMMARY

OBJECTIVES

The objectives were to:

1. Develop and test a transmission electron microscopy reference method for the quantitative analysis of asbestos fibres in bulk materials.

2. To develop and validate a routine optical method for the quantitative analysis of asbestos fibres in bulk materials.

3. A third objective added towards the end of the project was to further investigate the classification, identification issues which will affect the quantification of asbestos in bulk materials.

This final report summarises the work carried out to achieve the first two objectives and addresses the third objective in some depth by focusing on three research questions. These were:

What are the differences between amphibole asbestos fibres and other fibrous forms of asbestos?

How can these differences be exploited to produce a method which is capable of discriminating between asbestos and non-asbestos fibres?

Is this discrimination justified on health grounds?

MAIN FINDINGS

Methods have been produced for the EU project to both identify asbestos minerals by polarised light microscopy (PLM) and to quantify the asbestos mass content in bulk materials by using a combination of phase contrast microscopy and polarised light microscopy (PCM/PLM).

As the largest fibres contain most of the mass and only fibres > 1 um in width and >5 µm long can be routinely identified by PLM; optical microscopy appears a good choice for asbestos mass percentage analysis.

Accurate mass analysis also relies on having a good estimate of the fibre thickness and studies to measure the third dimension were undertaken, which showed that due

to preferential alignment the fibre depth on average is about 0.33 to 0.5 of the measured width for amphibole fibres. To calculate mass to within a factor of 2, it is only necessary to count, size and identify a representative sub-population of about 100 >5 um long fibres by PCM/PLM. Both the optical microscopy identification and quantification method were successfully tested for their precision and accuracy by two different inter-laboratory round robins, each consisting of two rounds in which 13 or more EU laboratories participated.

A reference method based on transmission electron microscopy (TEM) has been produced and tested in two interlaboratory round robins and can be used to give mass and fibre number results based on accurate chemical and crystallographic identification of all fibre sizes.

There are a number of problems associated with hazard assessment and the use of the proposed EU method for PCM/PLM mass analysis. It can be argued that if fibres are subject to a challenge (repeated one minute grinding periods in a ceramic mortar), to assess the releasable fibre content there will be no asbestos fibres >1 um width left, therefore any optical mass assessment is biased and may be based solely on non-asbestos mineral fragments resulting from cleavage of amphibole materials.

This led to an extensive investigation of the shape, mineral and chemical characteristics of asbestos and non-asbestos fibres. The main findings were that:

Accurate TEM length, width and aspect ratio measurements allow populations to be characterised and estimates of the asbestos and non-asbestos content to be made. This discrimination is much more effective when applied to >5 μm long fibres and samples containing mainly asbestos or mineral fragments. In many mineral samples the fibre growth may produce intermediate shapes or have mixed populations making individual fibre judgements very difficult.

Inspection of the ends of large fibres by scanning electron microscopy allows an estimate of how asbestiform the large fibres are due to the presence of many fibrils. SEM also has a 3D image which allows the cleavage faces to be more clearly seen.

In some ways PCM/PLM observations of >5 μm long fibres can approximately size the fibres and determine whether the fibre consists of fibrils due to its morphology and / or extinction angle. However , it cannot do this as accurately or as consistently well as the electron microscopy methods, and will with difficult samples consistently overestimate the asbestos content. This is acceptable if the PCM/PLM is used as a screening method and it is understood that further analysis may be required. There is also the possibility that a population of thin asbestos fibres is present which may have <0.1 % mass by weight but can still present a considerable asbestos exposure.

Fibre chemistry showed that the minor substitution of Al for Si, is associated with some of the more acicular fibres which do not appear to have the characteristic fibrillar structure of asbestos.

MAIN RECOMMENDATIONS

More field studies are necessary to determine the false positive and negative rates of the PCM/PLM method on real samples before hazard labelling based on this method alone takes place.

A study of some UK quarries and quarry products is needed to assess how much of a problem this may be.

The current EU stance on 'asbestos' to the exclusion of other amphibole fibres needs careful appraisal. All the evidence in recent years shows that durable fibres have a physical toxicity. Minor chemical substitutions, a mixed-population of mineral fragments and asbestos fibres or the degree of fibril growth within the larger fibres will be unlikely to reduce the toxicity of the long respirable fibres. Therefore potential carcinogenic fibres may be overlooked if we attempt to rigidly apply the criteria required for asbestos.

However, it would also be consistent to apply the results from the many animal experiments which show that respirable, durable fibres of the same length or greater than the macrophages are the most toxic and the most difficult to remove from the lung. Therefore the PCM/PLM hazard assessment should also record the numbers of >5, 10, 15 and 20 μm long respirable fibres produced by the standard challenge(per unit mass) in that this will allow a more precise assessment of the materials toxicity to be made. These data will require no additional work to collect.

Although labelling materials as carcinogenic if they contain more than 0.1% by mass of carcinogen is conventionally used in the EU, it does not make sense for carcinogens which have a physical toxicity. Fibre mass is largely determined by the contribution of a few relatively wide and possibly non-respirable, non-asbestos fibres. Therefore there is an anomaly that samples with the greatest measured hazard may actually manifest the least risk if made airborne and sampled by the European reference method.

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1. INTRODUCTION

1.1 The Problem

Asbestos continues to be a major cause of industrially related cancers in the UK (Peto et al. 1995, Hodgson et al. 1997). Lifetime risk to the male population born between 1940 -1950 are estimated to be as high as 1 in 100, with the annual deaths from mesothelioma forecast to rise from about 1000 in the early 1990's to a peak of up to 3000 mesotheliomas in 2020. Much of this rise is attributed to earlier use of asbestos due to the long lag time for the disease but any continuing exposure is of concern. This had lead to a tightening of the UK asbestos regulations in 1987,1992 and 1998 (proposed). However, asbestos exposure in the UK is thought to be due only to the importation of the bulk fibre for primary and secondary manufacturing, the installation of the asbestos containing products in building (e.g. thermal and fire protection insulation) and subsequently removal of such products. As asbestos is not mined in the UK very little attention has been given to the potential exposure from naturally occurring asbestos fibres in other minerals, which are either mined, quarried or imported into the UK.

A wide range of naturally occurring minerals have been reported to contain or be contaminated with asbestos fibres (see table 1). Mostly amphibole asbestos and in particular fibrous tremolite is present as the contaminant. The EU classifies asbestos as a category 1 carcinogen, which means that any substance or preparation containing more than 0.1% by mass of a carcinogen must be labelled and considered to be carcinogenic. This is recognised to be rather an arbitrary limit, as asbestos fibres present in a matrix at a concentration of 0.1% if ground to a fine powder and then made airborne, would greatly exceed the current control limits for airborne asbestos exposure. Mathematically, if the asbestos could be reduced to a uniform fibre dimensions typical of airborne asbestos concentrations (e.g. 10 μm long and 0.4μm diameter with a density of 2.5 $kg.m^3$ = a mass of 3.14×10^{12} g) each gram of finely divided material would contain 320 million regulatory asbestos fibres, if present at the 0.1% level by mass. If 1 g of this fine dust was made airborne and uniformly distributed in a 100 m^3 volume room (10 $mg.m^3$ dust concentration), an airborne fibre concentration of 3.2 f/ml would be produced. In practical experiments in animal exposure chambers it was shown that asbestos fibre mass concentrations in soil matrices need to be below <0.001% to not exceed the regulatory control limit of 0.2 f/ml (Addison et al., 1991). It should be stressed that the above represents the worst case situation but certainly it is likely such levels could be approached as peak exposures in mineral production and processing industries and poorly controlled environments in manufacturing industries.

The issue is not a new problem. In the US there was an intense debate between mineral producers and regulators for some 20 years between 1972 -92 which ended when OSHA reversed its previous stance and agreed to regulate non-asbestiform mineral fibres as a nuisance dust. However, this ruling did not end the controversy as OSHA was unable to give a method which could determine whether a fibre seen under the microscope was an asbestos fibre or not.

Table 1: Overview of minerals which may be associated with asbestos

Associations	Chry-sotile	Antho-phyl-lite	Tremo-lite	Acti-nolite	Grune-rite (Amo-sit)	Riebe-kite (Croci-dolite)
SULFIDES						
Sphalerite		X				
Galena		X				
Arsenopyrite	X					
Pyrite	X	X	X	X	X	X
Nicolite	X					
HALIDES						
Fluorile		X		X	X	X
OXIDES & HYDOXIDES						
Quartz	X	X	X	X	X	X
Magnetite	X	X	X	X	X	X
Haematite	X	X	X	X	X	X
Chromite	X					
Rutile	X	X			X	X
Ilmenite		X	X	X	X	X
Brucite (nemalit)	X					
CARBONATES						
Calcite	X		X	X		X
Magnesite	X		X			
Dolomite	X		X			
PHOSPHATES						
Apatite		X			X	X
Monazite		X			X	X
SILICATES						
1. Neso-silicates						
Olivine (forsterite)	X		X			
Olivine (fayalite)					X	
Garnet (almandin)				X	X	
Topaz		X				
Sphene		X			X	X
Zircon		X			X	X

Associations	Chry-sotile	Antho-phyl-lite	Tremo-lite	Acti-nolite	Grune-rite (Amo-sit)	Riebe-kite (Croci-dolite)
Sillimanite				X	X	
Andalusite				X	X	
Kyanite				X	X	
Chloritoid		X				
2. Soro-silicates						
Epidote			X			
Zoisite			X			
Clinozoisite			X			
Pumpellyite			X			
Lawsonite			X		X	
3. Cyclo-silicates						
Cordierite		X		X	X	
Tourmaline		X			X	
4. Ino-silicates						
Pyroxene: enstatite		X				
- : diopside			X			
- : hedenbergite					X	
- : aegerine						X
Amphiboles						
- : Anthophyllite				X		
- : Cummingtonite					X	
- : Grunerite					0	
- : Tremolite	X	X				
- : Actinolite					X	
- : Hornblende		X	X	X	X	X
- : Barkevikite						X
- : Glaucophane			X			
- : Riebekite						0
- : Arfvedsonite						X
Wollastonite			X	X		

Associations	Chry-sotile	Antho-phyl-lite	Tremo-lite	Acti-nolite	Grune-rite (Amo-sit)	Riebe-kite (Croci-dolite
5. Tecto-silicates						
Alkali-feldspar		X			X	X
Albite		X	X		X	X
Plagioclase	X	X			X	
Nepheline						X
Sodalite						X
6. Phyllo-silicates						
Muscovite		X		X		
Phlogopite			X			
Biotite		X	X		X	X
Zinnwaldite		X				
Stipnomelane			X			
Talc	X	X	X			
Chlorite	X	X	X	X	X	X
Chrysotile	0		X		X	
Lizardite	X		X		X	
Antigorite	X		X		X	
Sepiolite	X		X			
Montmorillonite	X	X	X	X	X	X
Kaoline	X	X	X	X	X	
Illite	X	X	X	X	X	
Vermiculite	X	X	X	X		

Table prepared for EU project by Ole Jorgensen.

1.2 Background to EU request for work

The essential focus of the work sponsored by EU funding arose through the work of DGXI over the classification of talc and talc containing asbestos in 1986 -88 for the Council Directive 67/548/EEC. It was agreed at the commission working group on the classification and labelling of dangerous substances 14-15 /9/1988, that talc fibres were not carcinogenic and therefore pure talc was non-carcinogenic. However, talc containing asbestos fibres would be classified as carcinogenic if asbestos was present over a certain amount. Discussions continued within the working group for a further 3 years on how to establish specific fibre concentration limits for asbestos in talc. It was eventually concluded that there was no method available to do this. This resulted in the inclusion to the 12th adaptation to Technical progress of the following final paragraph in section 1.7.2.1. (classification of substances containing impurities, additives or individual constituents) of annex VI," In the case of asbestos (650-013-00-6) this general rule does not apply until a concentration limit has been fixed in Annexe 1. Substances in which asbestos is present must be classified and labelled according to the principles in Article 6." It was also agreed that a request should be made to DGXII to commission the development of a test method to detect asbestos fibres in a talc matrix. The test method was expected to produce data on which a specific concentration limit of asbestos fibres (in bulk material) could be set.

A meeting was organised by BCR in June 1992 to discuss a possible test method and research programme at which approximately 24 laboratories or organisations were represented. This meeting was attended by the chairman of the DGXI committee involved (Dr Jim Hart) and the problem requirements discussed. This lead to a proposal being submitted and to the issue of a formal contract in December 1993 (MAT1-CT93-0003 Asbestos in bulk materials) co-ordinated by the Danish National Institute of Occupational Health (Arbejdsmiljoinstitut). An HSE/HSL representative attended this meeting and felt that the objective of a low cost light microscopy screening method, could be met by further development of the HSE funded work under contract R42.46 /2491 with the Institute of Occupational Medicine (IOM). This was the only method under development and had produced some data to show that it might work. IOM was therefore one of the partners developing the EU light microscopy method and their work was 50% funded by HSE, under contract R48:91 / 3210.

1.3 Background to HSL work

While supporting the need for a light microscope screening method, HSL was concerned that without a reference method, there would be no way of overcoming the uncertainties that would arise from the limitations of light microscopy. Also, more fundamental work needed to be undertaken, to resolve the difficult problems of defining asbestos. As EU funding was limited, some additional work was funded under the HSE project R42:70 to produce a TEM reference method, as well as to participate in the development and testing of a semi - quantitative light microscopy

method. One other important aspect of the work was also to produce an EU method for the identification of asbestos in bulk materials by l ight microscopy . In the initial EU discussions it proved difficult to convince the DGXII representatives that although the screening method might be able to measure the mass of the possible asbestos fibre content, it would not be able to positively identify the fibres were asbestos. Therefore a method for identifying asbestos, before attempting to quantify the fibres was an important precursor to the screening method.

1.4 Objectives

Project R42:70 therefore had two distinct objectives:

1. Develop and test a transmission electron microscopy reference method for the quantitative analysis of asbestos fibres in bulk materials.

2. To develop and validate a routine optical method for the identification and quantitative analysis of asbestos fibres in bulk materials.

A third objective was added towards the end of the project was to produce a report on the classification, identification and discrimination issues, which will affect the quantification of asbestos in bulk materials. This objective replaced an objective of producing a MDHS of the TEM reference method, whose cost could not be justified in terms of the potential market.

This final report discusses the investigations undertaken and results obtained for the three objectives above, in some detail. To place the work in context the issues involved in objective 3 are discussed first.

2. OCCURRENCE, DEFINITION AND CLASSIFICATION OF ASBESTOS

2.1 Occurrence

Amphibole and serpentine minerals occur frequently on the earth's surface (e.g. some 40% of the USA). Predominantly, amphibole minerals are found in metamorphic rocks but can also occur in igneous rocks and granites. Small inclusions of asbestos fibres may grow in the host rocks. The best formed amphibole asbestos fibres occur in cross-fibre veins of usually less than 25 mm width. Other occurrences of asbestos fibres are in pods and lenses, corresponding to slip-fibre with the fibres oriented along the ore body, with rather ill-defined lengths overlapping one another. Some deposits also occur in a more massive form in which small patches of parallel fibres are disposed in all orientations with respect to one another. Chrysotile asbestos usually occurs in serpentized ultramafic rocks (dunites and peridotites) and in serpentized

dolomitic marbles. Again cross-fibre veins formed during the serpentization is the main source of the asbestos fibres. When the concentration of asbestos to host rock is greater than 1-2%, and is present as a high grade fibre in an extensive deposit, commercial mining is feasible. At lower concentrations, or in smaller deposits the asbestos is regarded as a contaminant of the rocks, which may be mined or quarried for other minerals or uses.

2.2 Asbestos Definitions

There is no one simple definition applied to asbestos as each definition may stress one or more aspects (e.g. mineralogical, regulatory or commercial classification). A suggested definition is given below.

2.2.1 *Suggested definition of asbestos for hazard analysis*

Asbestos is a term applied to a number of amphibole minerals and one serpentine mineral, which due to metamorphic conditions have grown to form high aspect ratio particles (fibrils) which are loosely held together in a parallel orientation to form fibres.

The ideal chemical composition of some of the most common asbestos types are given in table 2.

Table 2: Varieties of asbestos, their non-asbestiform mineral analogues, and idealised end member compositions (adapted from Hodgson (1966) and Walton (1982)).

Asbestos Variety	Non-asbestos Mineral Analogue	Nominal Composition
(Serpentine group of minerals)		
Chrysotile	Lizardite, Antigorite	$Mg_3 (Si_2O_5) (OH)_4$
(Amphibole group of minerals)		
Crocidolite	Riebeckite	$Na_2Fe_3^{2+}Fe_2^{3+}(Si_8O_{22}) (OH)_2$
Fibrous grunerite (Amosite)	Grunerite	$(Fe^{2+})_7(Si_8O_{22}) (OH)_2$
Anthophyllite asbestos	Anthophyllite	(Mg, Fe^{2+}) 7 $(Si_8O_{22}) (OH)_2$
Actinolite asbestos	Actinolite	$Ca_2(Fe^{2+},Mg)$ 5 $(Si_8O_{22}) (OH)_2$
Tremolite asbestos	Tremolite	$Ca_2Mg_5 (Si_8O_{22}) (OH)_2$

2.2.2 *Mineralogical and chemical definition*

According to rules of procedure of the commission of new minerals and mineral names of the International Mineralogical Association (IMA), a mineral should be defined by its chemical composition and by its atomic structure. All other properties like morphology, colour cleavage, fracture and optical properties are secondary properties which can be used for identification if the chemical composition and atomic structure cannot be determined. Therefore asbestos are fibre formed minerals with a chemical composition and structure similar to the following minerals: serpentine, anthophyllite - gedrite, cummingtonite - grunerite, tremolite - ferroactinolite and riebeckite.

The chemistry of the amphibole group of minerals is very complex and has been the subject of extensive efforts by the IMA to achieve a classification system. The latest classification (Leake et al. 1997), is based on the chemical contents of the of the standard amphibole formula, $A\ B_2\ C^{VI}_5\ T^{IV}_8 O_{22}\ (OH)_2$ where A = 1 site per formula unit, B = 2 M4 sites per formula unit, C = A composition of 5 sites made up of 2 M1 sites, 2 M2 sites and 1 M3 site per formula unit, T = 8 sites in two sets of four, and 2 (OH) sites per formula unit. At each of the sites A,B and C various combinations of cations can be present, depending mainly on the size of the cations and the need to maintain a charge balance. The T site is normally occupied by Si but varying amounts of substitution with Al and more rarely Ti^{4+}. Extensive rules for classification into a particular group and mineral exist, but it is possible to arrive at different names depending on the procedure used to estimate the amounts of Fe^{2+} and Fe^{3+}. It is customary in the nomenclature to place the chemical divisions between minerals at 50 mole % but this division is not often followed in nature, where only distinct bands of percentage composition are found and a continuous solid-solution series is much rarer. Earlier classification used various percentages and in the latest classification only tremolite is not placed at 50%. This gives considerable scope for renaming of some previous asbestos minerals.

An example where the solid solution is continuous is the tremolite - actinolite - ferro-actinolite series where the $Mg/(Mg + Fe^{2+})$ ratio of greater than or less than 50% will decide whether the mineral is actinolite or ferro-actinolite. Also, if a relatively small amount of substitution of Si takes place at the T site and the Si in the formula reduces from 8 to <7.5, the mineral is now called a hornblende. Neither ferro -actinolite or hornblende minerals in their fibrous forms are regulated asbestos types in the EU.

Mineralogically the amphibole must have a structure based on a double silicate chain, a biopyribole consisting of equal numbers of pyroxene chains and triple chains would have the same chemical formula but would not be an amphibole.

2.2.3 *EU Regulatory definitions*

Most regulatory definitions of asbestos are restricted to a group of five amphibole minerals and one serpentine mineral (chrysotile), which have had some commercial

use. They are commonly referred to in several EC directives and adaptations (e.g. 91/659/EEC, 83/477/EEC, 92/32/EEC and 88/379/EEC) by their Chemical Abstract Service (CAS) numbers, the non-asbestos varieties are also listed for reference:

Asbestos variety	CAS number	Non- asbestos variety	CAS number
Actinolite asbestos	77536-66-4,	Actinolite	13768-00-8
Anthophyllite asbestos	77536-67-5,	Anthophyllite	17068-78-9
Amosite	12172-73-5,	Cummingtonite -Grunerite	14567-61-4
Chrysotile	12001-29-5,	Antigorite, Lizardite	12135-86-3
Crocidolite	12001-28-4,	Riebeckite	17787-87-0
Tremolite asbestos	77536-68-6	Tremolite	14567-73-8

The value and validity of the use of CAS numbers for EU definitions is arguable and this topic is dealt with in more detail in Appendix 1. It should be noted that the EU definition is limited to the asbestos types which have had some commercial exploitation. The three most commercially important types of asbestos have been given their own 'varietal' names: chrysotile, crocidolite and amosite and their non-asbestiform equivalents have different names. It must be emphasised that asbestos if present will represent only a small fraction of the non-asbestos variety of the mineral.

2.2.4 *UK Regulatory definitions*

The UK asbestos (prohibitions) regulations 1992 (SI 3067:1992) says "asbestos" means chrysotile ,and amphibole asbestos and any mixture containing any of those minerals. Where "amphibole asbestos" means any of the following minerals, namely crocidolite, amosite, fibrous actinolite, fibrous anthophyllite, fibrous tremolite and any mixture containing any of those minerals. The control of asbestos at work regulations (CAWR, revised 1992) says, "asbestos means any of the following minerals, that is to say crocidolite, amosite, chrysotile, fibrous actinolite, fibrous anthophyllite, fibrous tremolite and any mixture containing any of those minerals. The UK prohibition of amphibole asbestos as currently written would therefore extend to any substance contaminated with any amphibole asbestos.

2.2.5 *International Standards Organisation definition*

The international standards organisation (ISO,1995) after a plenary session adopted the following definition for asbestos, "Asbestos is a collective term applied to specific serpentine and amphibole minerals which have been crystallised in the asbestiform habit, causing them to separate into long, thin , strong fibres when crushed or processed. The most common forms are....." the EU regulated varieties as in 2.2.3.

2.2.6 *Other asbestos definitions*

Many other definitions for asbestos that have appeared in print (e.g. Campbell et al., 1977, Dana, 1970, Deer et al., 1963, Hodgson, 1966, Langer et al. 1991, OSHA, 1971, 1992, 1994, Ross, 1978, Walton, 1982), often combining the mineralogical / morphological description with one or more of the useful commercial or physical properties of the fibres, such as: a good insulator, capable of being woven into cloth, high flexibility, high tensile strength and capable of separating the fibres easily. Although these properties cannot be used as a method for the identification of individual asbestos fibres, they have been used as an argument for saying that some rock deposits contaminated with mineral fibres are not asbestos-containing, because they lack these secondary or commercial properties.

A term byssolite is the mineralogical name used for hornblende fibres but has also been used to describe the non-commercial grade amphibole deposits (Dana,1970, Dorling et al. 1987). This secondary use, is however rather an arbitrary distinction, as textile grade asbestos fibres were not produced by all of the commercial asbestos mines.

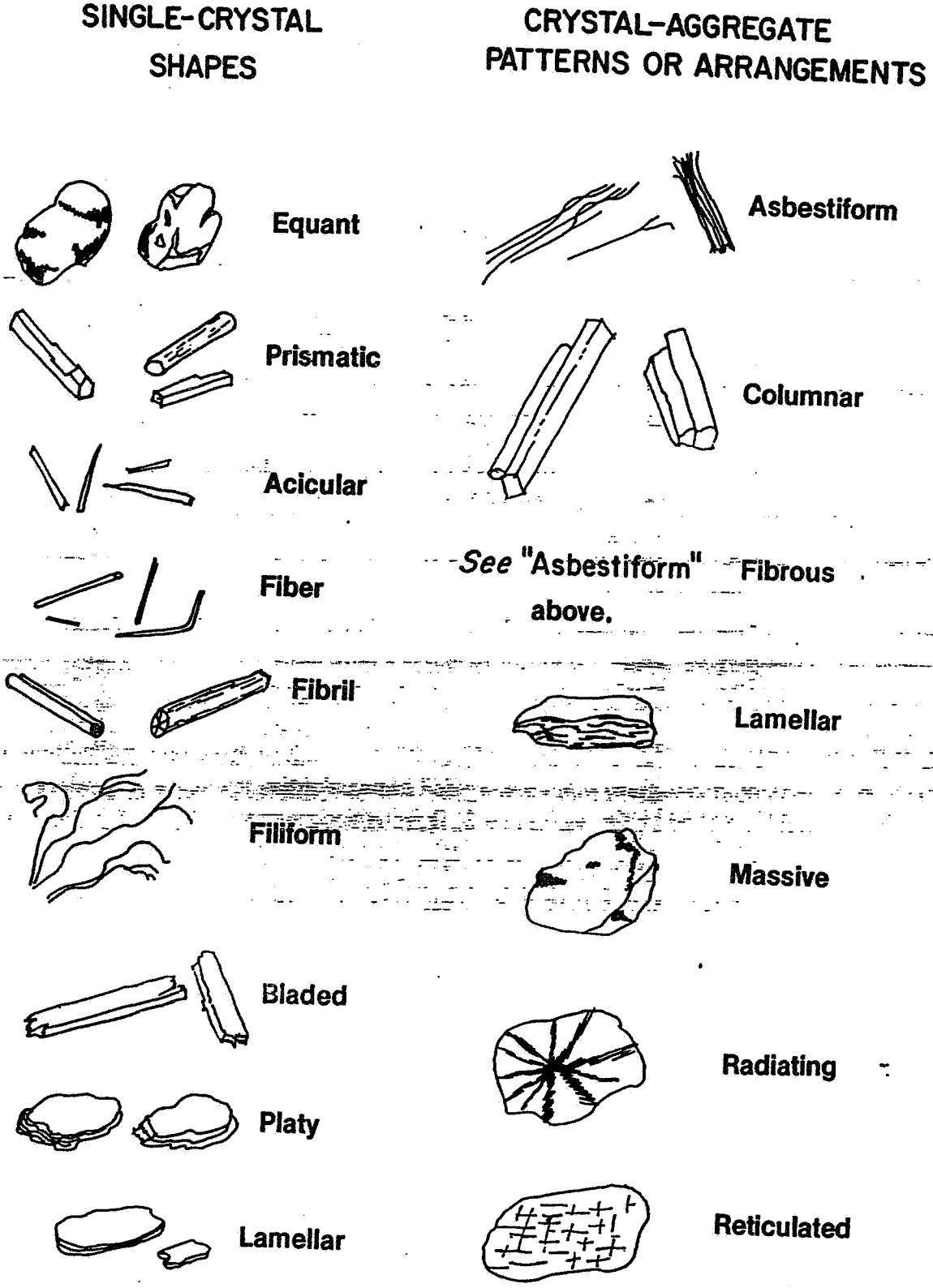
2.2.7 *Definitions used to describe particle shape.*

The shape of the particles is the primary observation made to determine whether the particle is asbestos. The definitions of the descriptors for particle shape are not well-defined. A typical description of the range of single crystal shapes is; equant, prismatic fragments, (stubby prisms -elongate prisms) acicular-coarse splintery fibres - fine fibres -asbestiform fibres. A similar progression is used to describe crystal aggregates. Campbell at al. (1977) attempted to clarify the situation and the system they used is reproduced as figure 1. Fibrous is a general term used to describe a mineral which occurs in a bundle of fibres. A fibril is used to demote a single fibre which cannot be separated into smaller components . Fibre is a general term to denote a elongated particle which appears to have grown individually into that shape, it may contain fibrils. Other terms such as asbestoid and amphobolic have also been used

2.2.8 *Morphological definitions used to evaluate airborne asbestos fibres*

When detecting small amounts of asbestos by microscopy, it is the morphology of the particles that is used as the initial identifying feature. Unfortunately, several morphological conventions have been applied to assess asbestos fibres depending on: the method being used, the matrix containing the asbestos and whether the risk or hazard is to be determined. The current definitions used for optical counting of airborne asbestos fibres as a index of risk, were developed largely by the asbestos industry in the 1950's as described by Walton (1982). There was an arbitrarily decision to define a fibre as a particle with an aspect ratio (length to breadth) of >3:1, with a minimum length of 5 μm (based on experimental and practical considerations) and a maximum width of 3 μm based on the ability of the fibre to penetrate into the deep lung (respirable). There has been much debate on the definition of a fibre but it's one (and possible only) virtue of the current one is that

Figure1:. Various shapes of single crystals, and patterns or arrangements of crystal aggregates, after Campbell et al. 1987.



it has remained unchanged for the last 30 years or more. In reality, even the use of a standard morphology has not meant that a count carried out on identical sample some 30 years ago would give the same result as now, as changes in the sample preparation method and counting protocol, have generally produced an increased fibre count with time (Walton, 1982; Rickards, 1995).

Analytical electron microscopy allows smaller fibres to be seen and either identified or classified. Several international standard (ISO) methods have been prepared (ISO 10312:95, ISO 13794:1998, ISO DIS 14966). Only the analytical transmission electron microscope (TEM) allows all asbestos fibres to be measured and identified. For ambient air measurement of asbestos by TEM an aspect ratio of 5:1 for counts of asbestos structures >0.5 µm in length has been used in ISO standards, although all ISO standards allow the use of a 3:1 aspect ratio when counting >5 µm long fibres or optically equivalent fibres (>5 µm long fibres and >0.2 -<3.0 µm wide). It should be noted that there are no standard EM methods for lung samples and different laboratories and researchers use both SEM and TEM to count parts of the size distribution, making inter-comparison difficult.

2.2.9 *Morphological definitions used to evaluate bulk asbestos fibres*

Over the last 20 years there have been a number of attempts to produce detailed descriptions / definitions of bulk asbestos fibres, as seen in a rock, soil or other solid matrices. One of the first and most authoritative attempts was by the US Bureau of mines (Campbell et al. 1979). The mineral industry (Kelse and Thompson, 1989) and various sponsored researchers (Wylie, 1990) have also promoted both the need for and methods to discriminate between asbestos containing and non-asbestos containing mineral or rock deposits, which are being commercially exploited. These definitions try to define an asbestos population ,by the morphology that would expected in its natural or refined states, when viewed under a optical microscope. The definition used in MDHS 77 is based on this earlier work and is reproduced below, along with the appropriate caution as to when it should be applied:

Under a light microscope, the asbestiform habit is generally recognised by the following characteristics:

A range of aspect ratios ranging from 20:1 to 100:1 or higher for fibres longer than 5µm;

Capability of splitting into very thin fibrils;

Two or more of the following:

- Parallel fibres occurring in bundles,
- Fibre bundles displaying frayed ends
- Fibres in the form of thin needles,

- Matted masses of individual fibres, and/or
- Fibres showing curvature.

Most individual fibres in samples of airborne asbestos and many asbestos fibres which have been ground in a matrix will not show the bulk characteristics above when viewed by optical microscopy. Therefore the above definition can only be applied to determine whether a population of asbestos fibres is present in a bulk sample."

3. HAZARD AND RISK MEASUREMENT OF ASBESTOS

3.1 Definitions

These terms again have a number of definitions applied to them (even within HSE) and even more confusion is generated when these are translated into various European languages and cultures. The issue is further compounded by the use of the term dangerous in EU directives, for example the Dangerous Substances Directive (67/548/EEC) and the Dangerous Preparations Directive (88/379/EEC). Within this current paper 'hazard' is used when we are trying to assess the potential to do harm and risk is used when assessing the probability of the hazard producing a detrimental health outcome.

3.2 Measurement of the hazard from asbestos

Ideally, for hazard evaluation, all asbestos fibre in the bulk sample should be assessed, regardless of size or its ability to be released. This is because further processing may result in comminution which will release greater numbers respirable airborne fibres, resulting in a increased risk. Therefore a large bundle of asbestos fibres with an aspect ratio below 20:1 and a width greater than 3 µm should not be excluded from the analysis of hazard because it doesn't fit either the most widely used air or bulk definitions for asbestos fibres.

3.2.1 *Problems with cleavage fragments and other morphological types.*

There is one very difficult issue that arises when attempting measure the asbestos risk or hazard of amphibole asbestos. All amphibole minerals due to their crystal structure have perfect {110} cleavage with a 56° or 112° angle between cleavage faces or cracks (Deer et al, 1963). There is also parting on the (100) due to defects and twinning which tends to form lath like particles (Dorling and Zussman, 1987). This means that when any amphiboles rocks are crushed, they have a tendency to form elongated cleavage fragments some of which may have aspect ratios > 3:1. However, the situation is even more complex, as the special conditions which favour the growth of asbestos may not be fully achieved throughout the deposit or only partially achieved at best. This still allows some preferential growth along the c-axis to form a range of